Multi-TSO system reliability: cross-border balancing

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Background

- GARPUR - an FP7 research project developing probabilistic reliability criteria in transmission
- This paper grew out of multi-TSO considerations within that project
    - TSOs must deal with imbalances in real time
    - Imbalances exacerbated due to increased penetration of intermittent solar and wind generation
    - In addition, available reserves should also be able to deal with large and sudden imbalances caused by failures of transmission or generation components.
    - Transmission networks are interconnected between different countries
    - Imbalances due to intermittent power increase, so number of unscheduled flows rises
    - Trend increases both need for reserves and costs for procurement and dispatch of these reserves
    - This paper shows that cooperation between adjacent TSOs on reserves dispatch and procurement can reduce this cost

Related literature

- Bjorndal et al (2015). Case-study example on balancing between Belgium and Netherlands
- Meeus et al. (2005). A more general conclusion, *viz.* that coordination of European balancing markets done by TSOs should be one of the next steps towards the harmonisation of electricity markets into the EU Internal Electricity Market
- van der Weijde and Hobbs (2011). Discuss similar issues and quantify the benefits of inter-market benefits using a stylised 4-node network
- Van den Bergh et al. (2015). Quantify benefits of cooperation and transmission constraints
- But still lack of understanding of economic efficiency aspects of network codes regarding TSO cooperation on reserves and balancing
- Reliability criteria impose levels of required reserves without any reference to balancing the costs of reserves and interruptions

Our paper

- Stylized framework, background in network codes
- Presents a probabilistic model that analyses three degrees of TSO cooperation in reserves provision
    - Autarkic TSO reserve provision
        - non-cooperative TSO equilibrium
    - Reserves exchange
        - allows for efficient procurement of given reserve capacities, but nor sharing of reserves
    - Reserves sharing
        - amounts to maximising the surplus of the two nodes jointly
        - allows both a cost arbitrage and pooling of reserve needs
- Show reserves sharing is economically superior to reserves exchange
- Numerical example in order to provide an illustration of the three scenarios.

Paper gives brief background on network codes

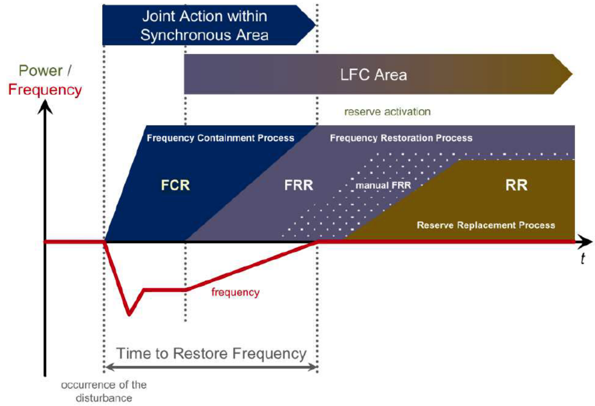

Fig. 1. Role and sequence of activation of the different reserve products: FCR, aFRR, mFRR and RR [15]

- ... but we abstract from the details in our model

Model

- Two TSO zones $i = 1, 2$
- Need for reserves in Zone i at a certain instant: r_i [MW].
- Imbalance in real time due to forecast errors of demand, intermittent supply, failures of generation capacity or transmission components
- Joint probability density function of the reserve needs r_i by $f(r_1, r_2)$
- r_1, r_2 non-negatively correlated and jointly normal with known parameters
- TSO's variable of choice is R_i [MW], the quantity of reserves procured
- Reserve capacity costs $\gamma_i(R_i)$, increasing, smooth and convex.
- Abstract from
    - different kinds of reserve products
    - efficient dispatch - set marginal generation costs to zero
    - transmission constraints

Order of events

- Ex-ante (before uncertainty is realised):
  - TSO i chooses how much reserve capacity R_i to procure
- Ex-post (after uncertainty is realised):
  - In real time the actual need for reserves r_i is observed in each node i
  - The procured reserves will be used to accommodate the reserve needs. In case local reserves are insufficient, TSOs will use exchanged or shared reserves, or shed load
  - [Settlement payments are made]

- Note: choice of reserve capacity could be for different time horizons, e.g. for an hour, a week, a month, or a year
- $f(r_1, r_2)$ will in general depend on the procurement interval and the time to real time operation
- In case of exchange or sharing of reserves, the procurement entails payments between TSOs - we do not model these payments

Autarkic TSO reserve provision

- Each zone is an "island" - TSO i maximizes:

$$E[S_i] = v\left(D_i - \int_{R_i}^{\infty}(r_i - R_i)\,f(r_i)\,dr_i\right) - \gamma_i(R_i)$$

- FOC:

$$v\,\Pr\{r_i > R_i\} = \gamma_i'(R_i)$$

- Intuition: reserves are procured up to the point where marginal cost of interruptions = marginal cost of providing that level of reserves
- Easily seen that the second-order condition for maximum of $E[S_i]$ is satisfied
- Optimal level denoted by $R_{i,a}^*$

Reserves exchange

- TSO can purchase part of required reserves in adjacent TSO zone
- Load-shedding if $r_i > R_i$, irrespective of where reserves are procured
- Exchange of reserves only allows cost arbitrage, not pooling of reserve needs
- Assume, cf. network codes, that required reserves in each TSO zone are same as in autarky $R^*_{i,a}$
- Assume TSOs jointly minimize total costs of procurement, subject to constraint on reserves

$$\min_{R_1,R_2} \gamma_1(R_1) + \gamma_2(R_2) \text{ s.t. } R_1 + R_2 = R_1^* + R_2^* \Rightarrow$$

$$\begin{cases} \gamma_1'(R_1) = \gamma_2'(R_2) \\ R_1 + R_2 = R_1^* + R_2^* \end{cases}$$

- Costs are lowest when marginal costs of reserve procurement are equal across zones

Reserves exchange: illustrative example

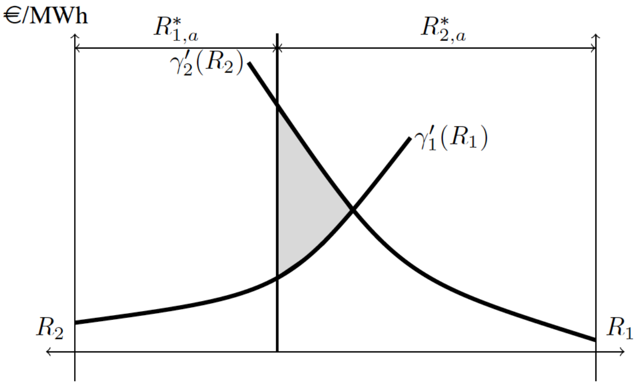

Fig. 2. Cost minimization under reserves exchange between two TSO zones

Reserves Sharing

- Allows multiple TSOs to draw on same reserves to meet required level of reserves when it comes to operation
- Allows both cost arbitrage and pooling of reserve needs, including sharing of interruptions if necessary
- Load shedding only if $r_1 + r_2 > R_1 + R_2$
- Amounts to maximizing joint surplus, i.e. maximizing

$$E[S_1 + S_2] = \quad v\left(D_1 + D_2 - \int_0^\infty \int_{R_1+R_2}^\infty (r_1 + r_2 - R_1 - R_2) f(r_1, r_2)\, dr_1 dr_2\right) - \gamma_1(R_1) - \gamma_2(R_2)$$

- FOCs

$$\begin{cases} v \Pr\{r_1 + r_2 > R_1 + R_2\} = \gamma_1'(R_1) \\ v \Pr\{r_1 + r_2 > R_1 + R_2\} = \gamma_2'(R_2) \end{cases}$$

- Marginal costs equal at optimal levels
- Costs of reserves procurement minimized as in reserves exchange, but for different levels of reserves and, hence, also reliability

Comparison

- Assume less than perfect symmetry in costs and less than perfect correlation
- Can show that overall social surplus improves with each step in integration:
  - autarky < exchange < sharing
- But distributional consequences: reserves costs will fall in one zone and rise in the other
- Similar for reserve sharing: distributional consequences both for costs and expected interruptions
- A minimal side payment is required in both cases to make exchange/sharing *incentive compatible*
- A bargaining problem - not considered in this paper

Numerical illustration

- Jointly normal reserve needs; in each zone: mean 10 [MW], variance 5 [MW]
- Quadratic cost of reserves $\gamma_i(R_i) = c_i R_i^2$
- Correlation coefficient ranging from 0 to 1
- Broad results:
    - More cost reduction when reserve procurement costs more asymmetric and reserve needs less correlated
    - With low cost asymmetry and low correlation, reserves sharing yields the major part of the cost reduction
    - With high cost asymmetry and a high correlation, reserves exchange yields the major part of the cost reduction
    - With symmetric costs and high correlation, crossborder cooperation in reserves yields very little cost reduction

Numerical illustration

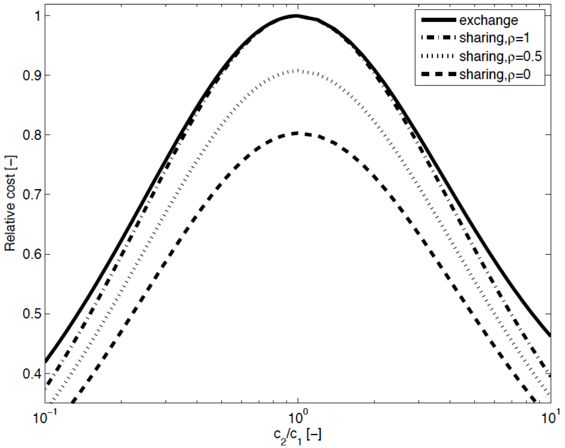

Fig. 3. Relative cost (compared to autarky) with reserves exchange and reserves sharing, as a function of the cost asymmetry and the correlation ρ between the reserve needs.

Concluding comments

- Compare three degrees of TSO cooperation in generation reserves provision: autarky, reserves exchange and reserves sharing
- Derive analytically, in a stylized model, optimal procurement of reserves in each case
  - costs, which are expected to rise with increasing penetration of renewable generation, decrease with cooperation
- Benefits of reserves exchange and reserves sharing depend on cost asymmetry and correlation of reserve needs
- With highly asymmetric reserve procurement costs but highly correlated reserve needs, reserves exchange yields a high cost reduction
- With fairly symmetric reserve procurement costs but a low degree of reserve needs correlation, reserves sharing is needed to reap the full benefits of TSO reserves cooperation
- Plenty of issues to consider in future research on this topic

Appendix slide: Table II

$c_1 = c_2 = 2$	R_1	R_2	$R_1 + R_2$	RR	TC	RC
Autarky	15.05	15.05	30.10	100%	998.4	100%
Exchange	15.05	15.05	30.10	100%	998.4	100%
Sharing	13.63	13.63	27.26	90.5%	801.7	80.3%
$c_1 = 4,\ c_2 = 2$						
Autarky	14.46	15.05	29.50	100%	1431.9	100%
Exchange	9.83	19.67	29.50	100%	1303.7	91%
Sharing, $\rho = 0$	8.97	17.95	26.92	91.3%	1046.1	73.1%
Sharing, $\rho = 0.5$	9.46	18.93	28.39	96.2%	1178.8	82.3%
Sharing, $\rho = 1$	9.87	19.74	29.61	100.4%	1295.3	90.5%